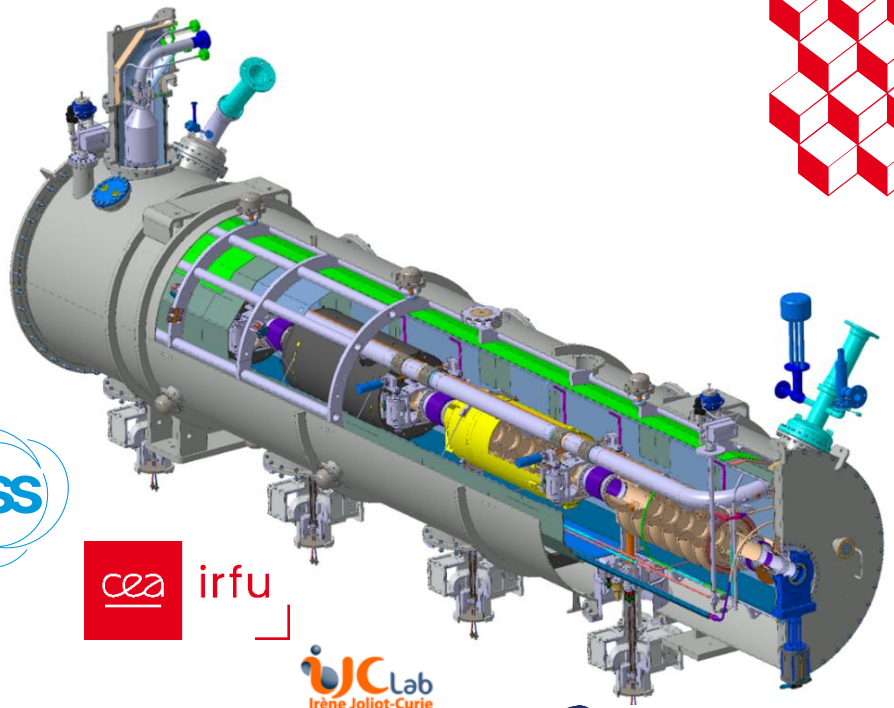
Analysis of parasitic emission phenomena during cryomodule operation

G. Devanz

with contributions of E. Cenni and ESS SRF team

TTC 2026 meeting WG2



ESS elliptical cryomodule operation

- **CEA-Saclay CM test stand (2018 → 2022)**
- **ESS Test Stand 2 (2021 → ...)**
- **Linac operation with short proton beam (2025→ ...)**

Various radiation-related behaviors have been observed:

- photoneutron emission in HB cavities

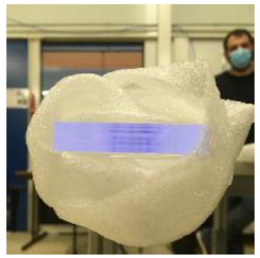
  FE → Bremsstrahlung → GDR Nb → ^{92m}Nb → γ decay (λ = 10.15 d , γ 934.5 keV)
- cryomodule activation
- neutron capture γs observed on NaI(Tl) spectrometer
- FPC e- activity → e- capture and acceleration → Bremsstrahlung
- Spurious FPC arc detection signals intiated by several sources of γs

  γ → ionization in optical fibers → Cherenkov if above $E_{threshold}$ → guided to arc detector
- Multiple, simultaneous FPC arc interlock spurious triggering can occur :
  - interlocks idle FPCs (proves the point)
  - serveral tens of FPC triggered up to 68 in a single event in the tunnel
  - still under investigation
- beam-losses related spurious arc detector signals

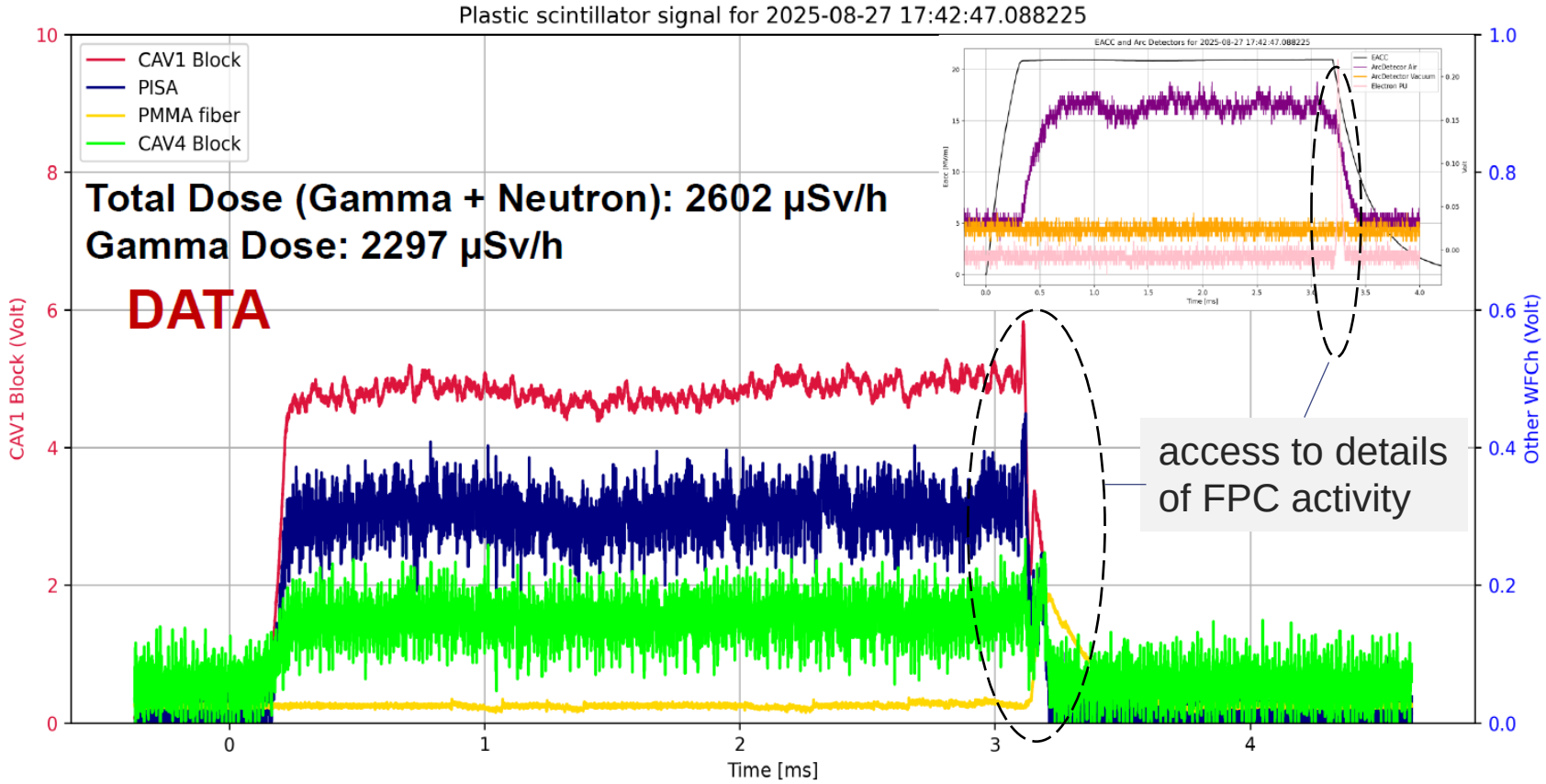
The sequence of processes was established by comparison of measurements to Geant4 modeling of the CM, test stand, tunnel, progressively adding details.

Identifying possible scenarii requires more than just a few area dosimeters : time resolution and energy information is invaluable

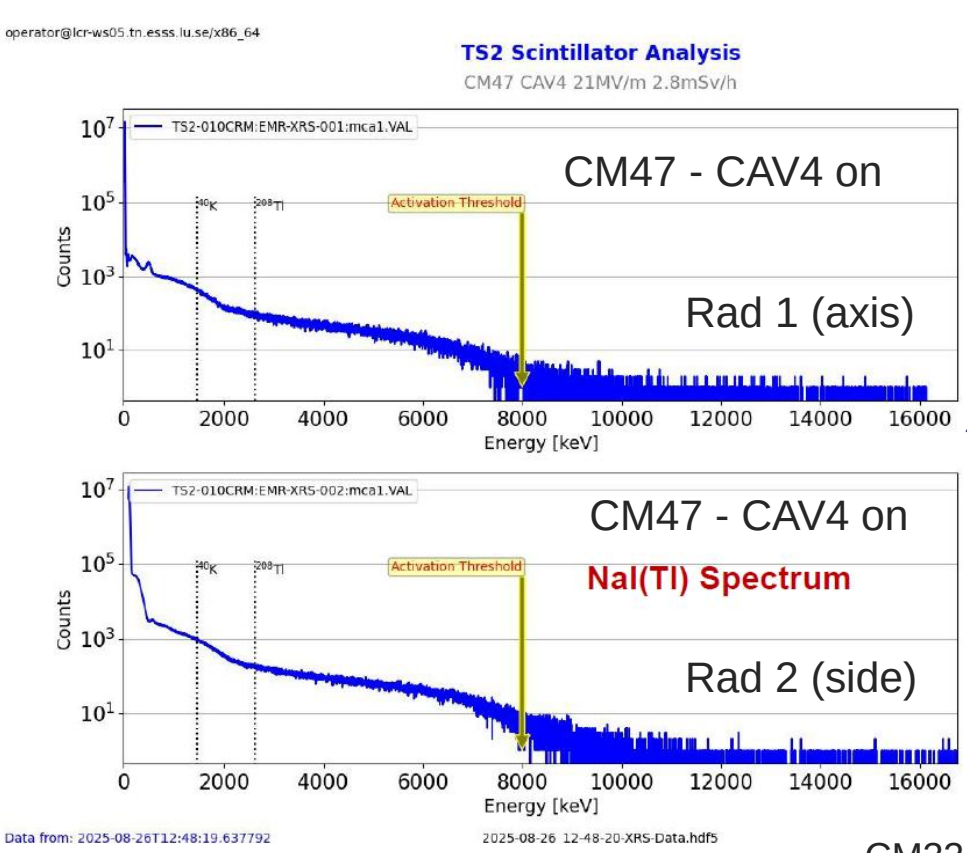
Instrumentation in the test stands (time resolution)



- plastic scintillator tiles or blocks (PVT) + PMT :
  - few µs time response with integrating electronics (as used for FPC interlocks)
  - few ns time response with TIA and direct signal recording (photon counting)
- PMMA fibers used as Cherenkov radiators (weak signal)

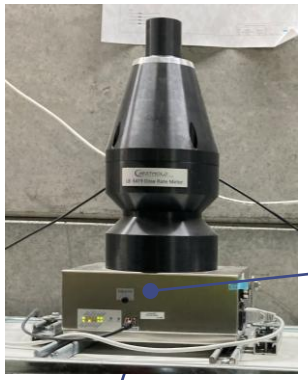


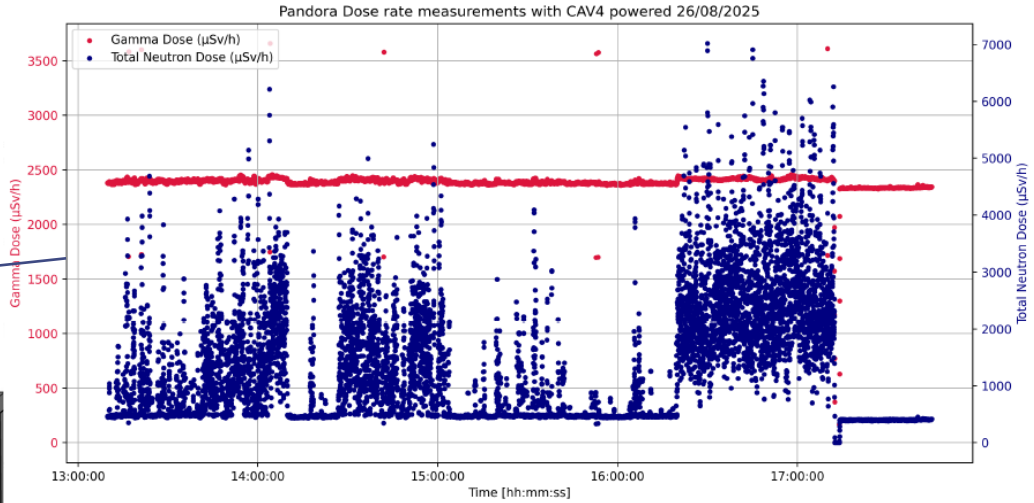
Instrumentation in the TS2 (energy, neutrons)

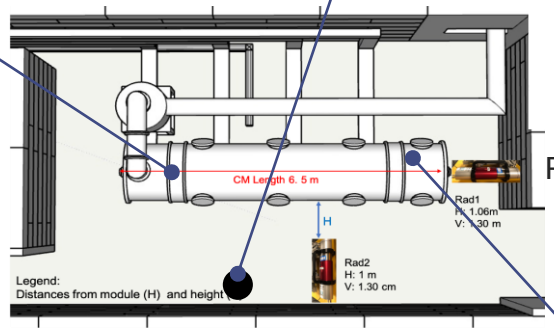


Data : C. Maiano

Pandora
LB6419
n + γ





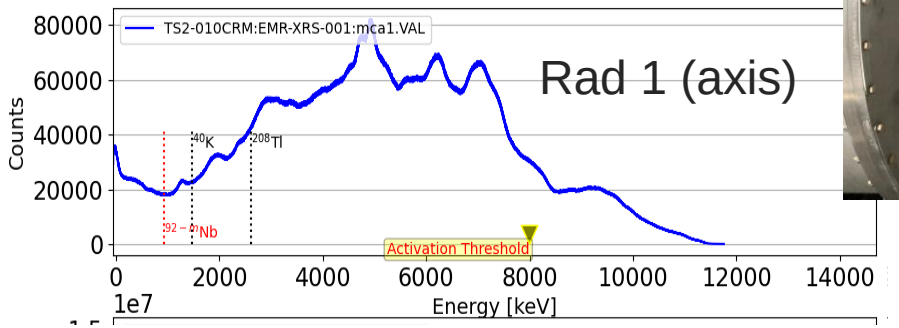


Rad 2
(side)

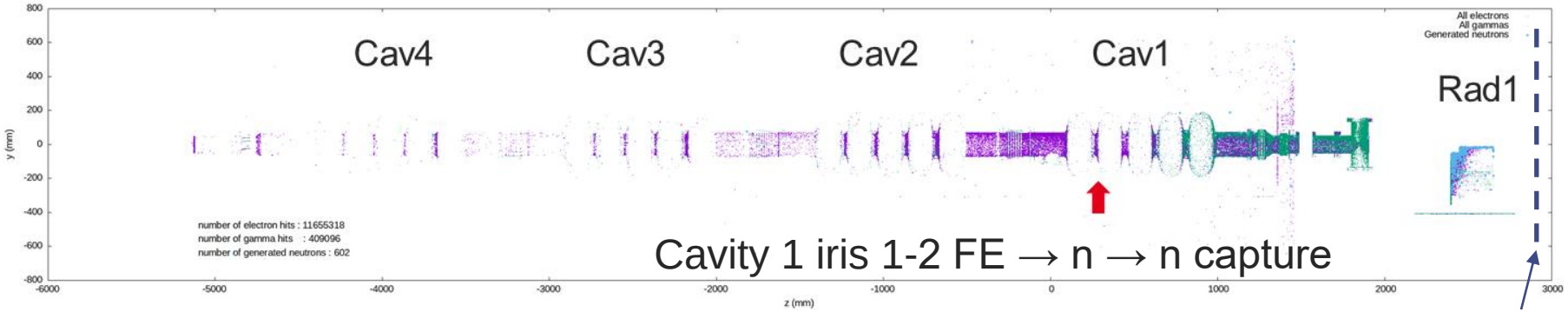
Rad 1 (axis)

CM33 - CAV1
E_{acc} > 22 MV/m

Bremsstrahlung
+ neutron capture
disctrete γ
spectrum

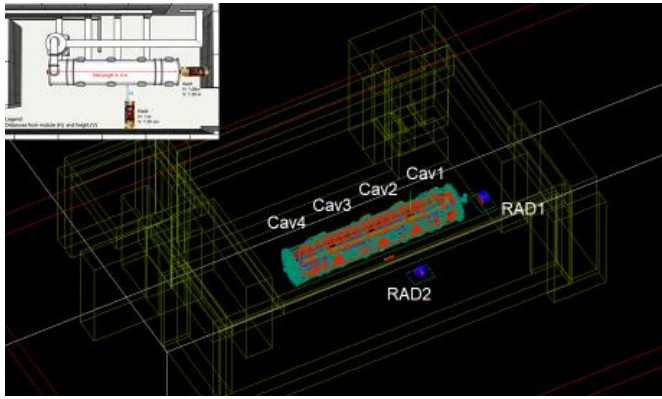


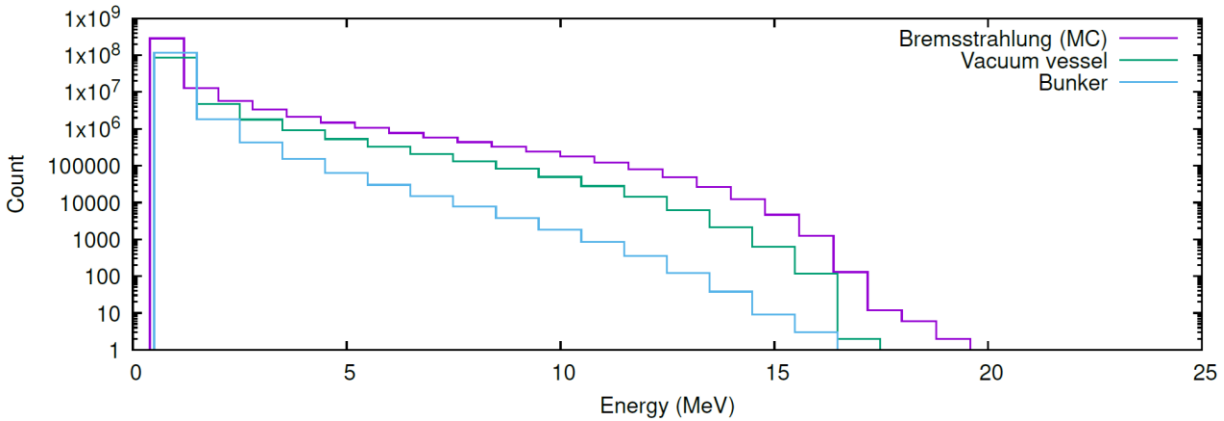
Geant4 simulated scenarii

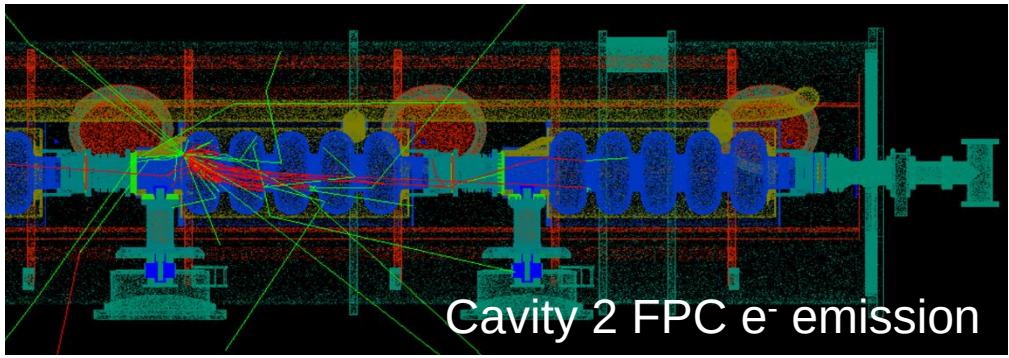


Cavity 1 iris 1-2 FE → n → n capture

bunker wall



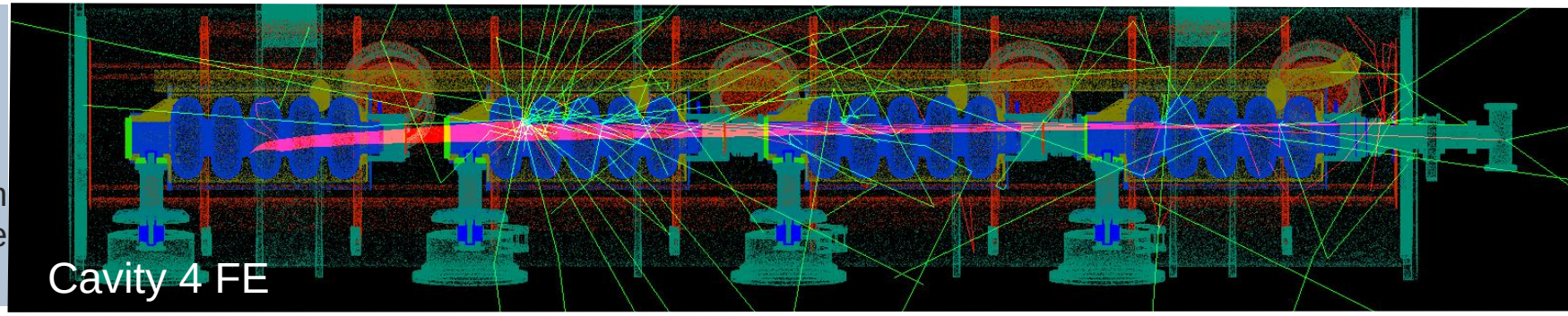




Main considerations for the choice of a scenario:

- Bremsstrahlung end energy
- main direction of radiation
- neutron/no neutron emission

The righ choice of scenario predicts the region where activation is to be expected on the cryomodule



Current concern : Spurious FPC arc detection

- Contribution of cavity FE
- Contribution of FPC_n electronic activity on FPC_m AD

  (mitigated by HV-bias)
- Indirect contribution of neutrons

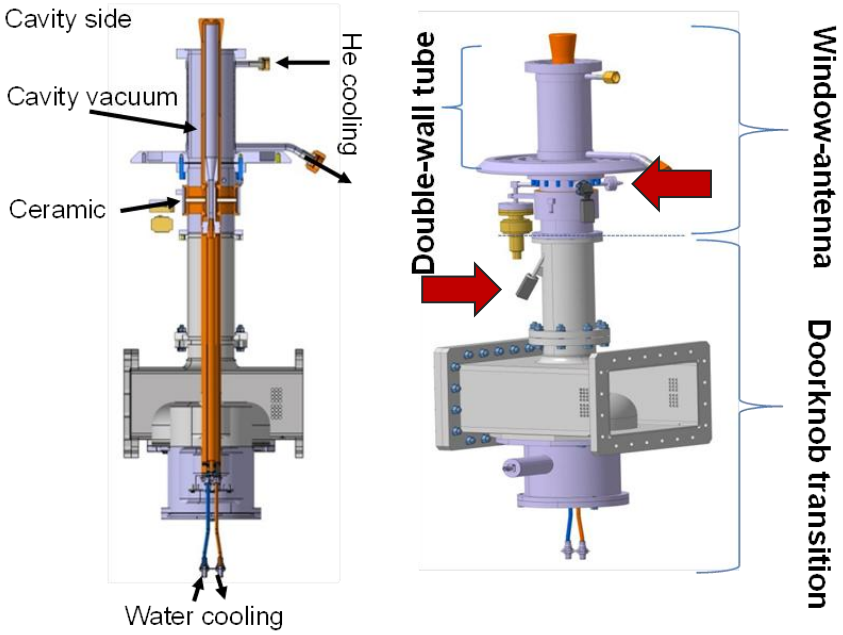
FPC arc detection

704 MHz FPCs
- **P_{peak} = 1.1 MW**
- **5% DC**

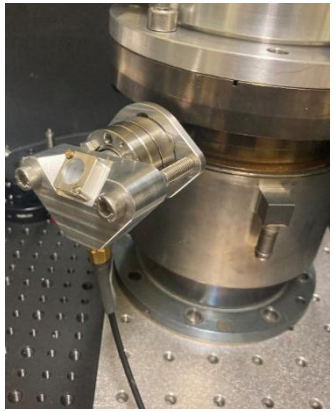
- **CEA test stands**

  Arc light detected by PMT modules mounted on viewports

- **ESS TS2 and linac tunnel**
  - PMTs are located in Arc Detection Unit (ADU), outside of radiation area
  - Light is transmitted from FPC to ADU using PMMA multimode optical fiber



2 Arc detection viewports



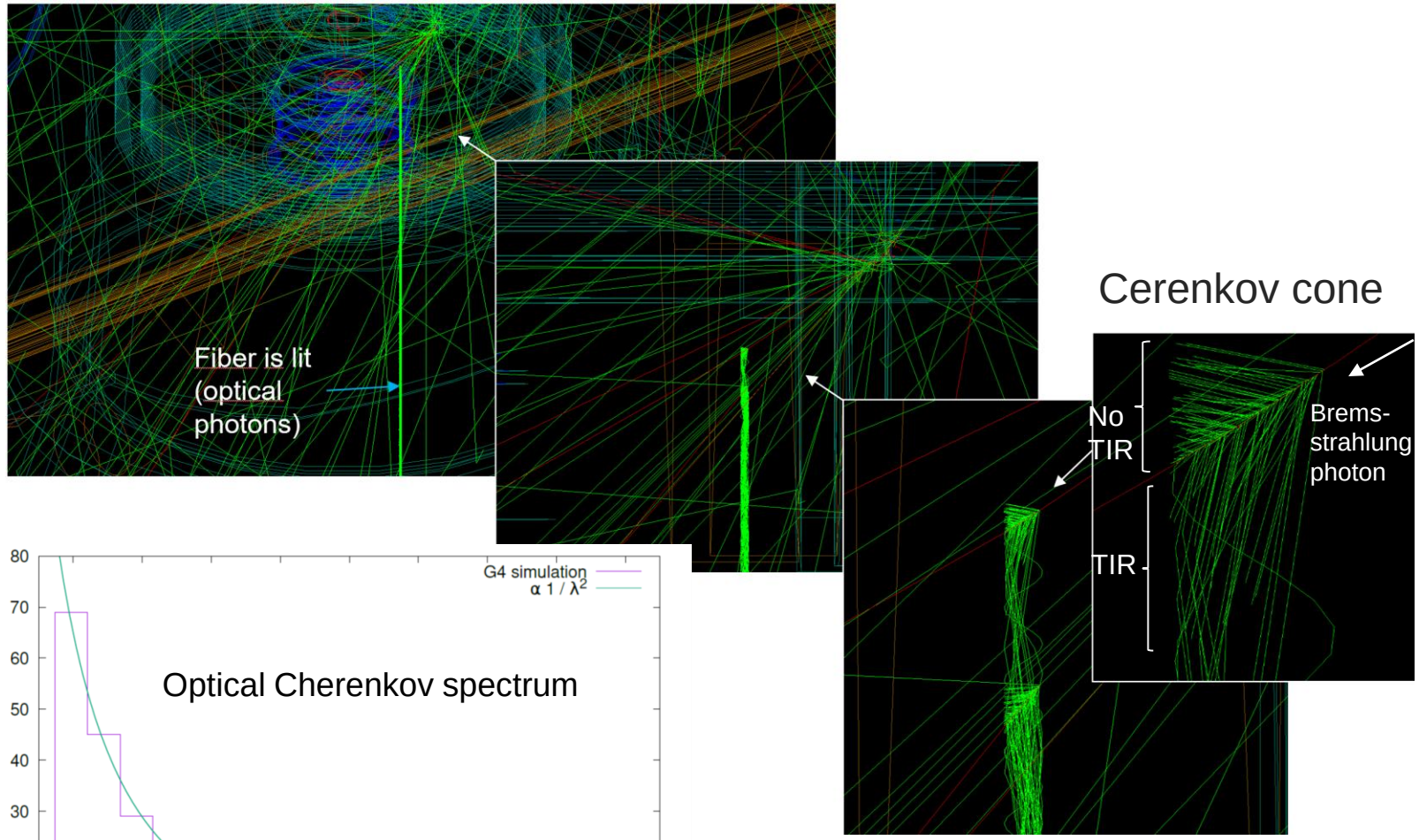
Optical fiber adapter

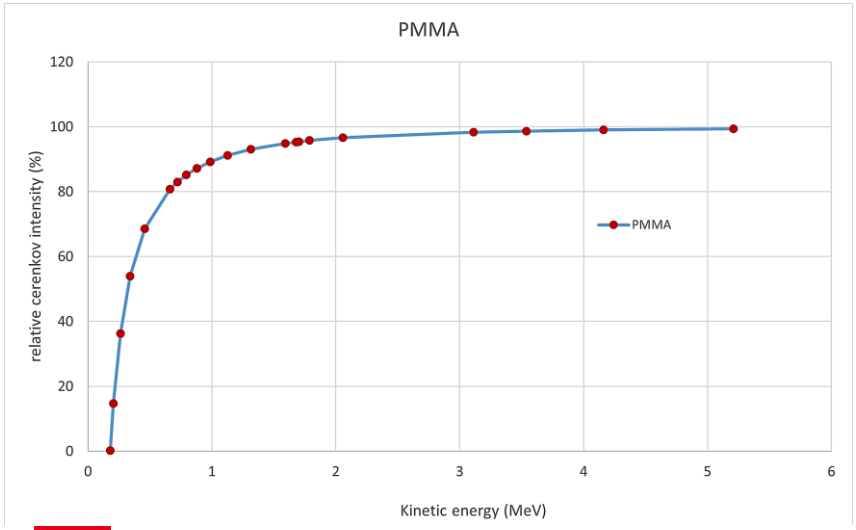
ESS Arc Detection Unit (ADU)

Contamination of arc signal by CM radiation generates spurious coupler interlocks
Most concern about sudden radiation burst from yet unidentified precise origin, observed during CM tests

Cherenkov radiation in FPC PMMA fibers

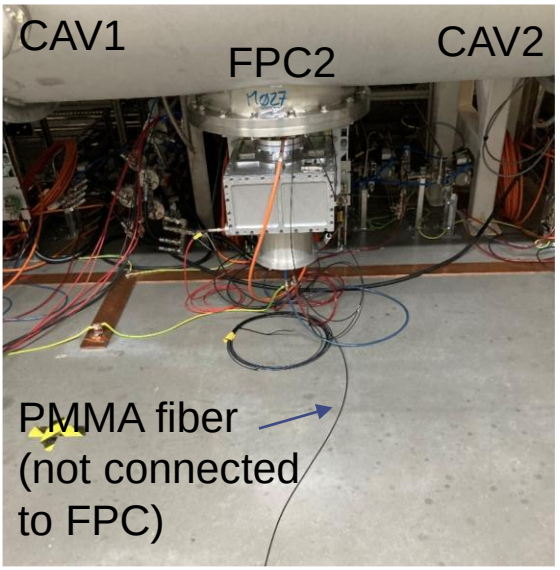
- HB Bremsstrahlung photon energy spectrum extends up to ~16 MeV at nominal gradient
- possible ionization/Compton scattering/pair creation inside fiber core or cladding
- Cherenkov threshold for e^+/e^- :180 keV in PMMA (n = 1.49)
- TIR angular condition → partial transmission in the fiber
- Geant4 generates and propagates the corresponding photons

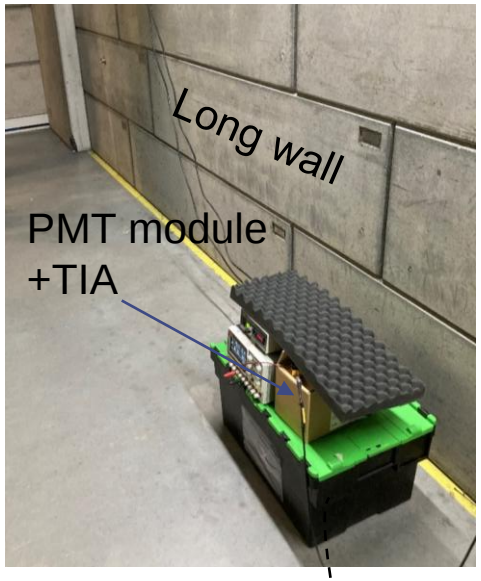


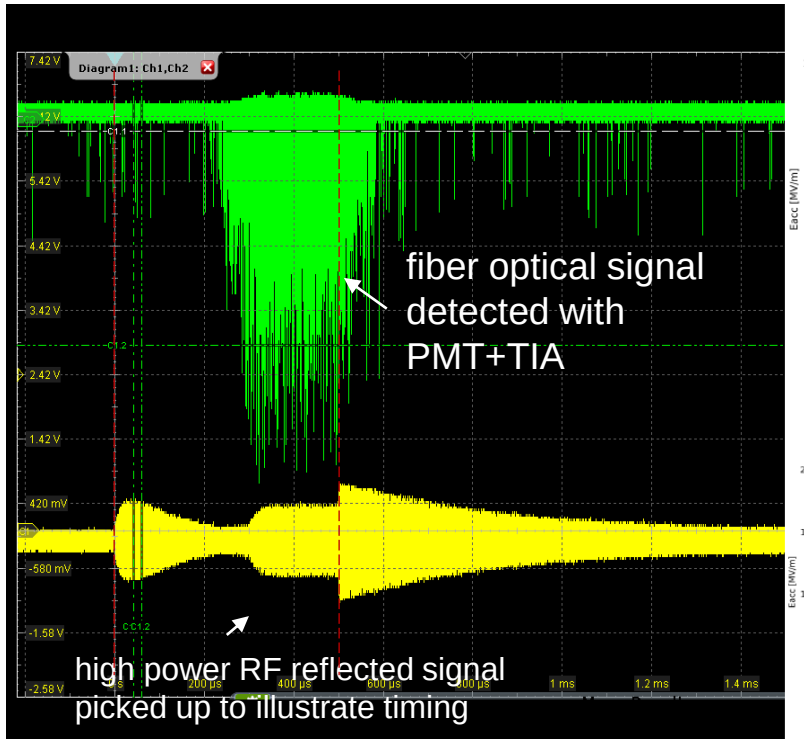


Cherenkov radiation in FPC PMMA fibers in TS2

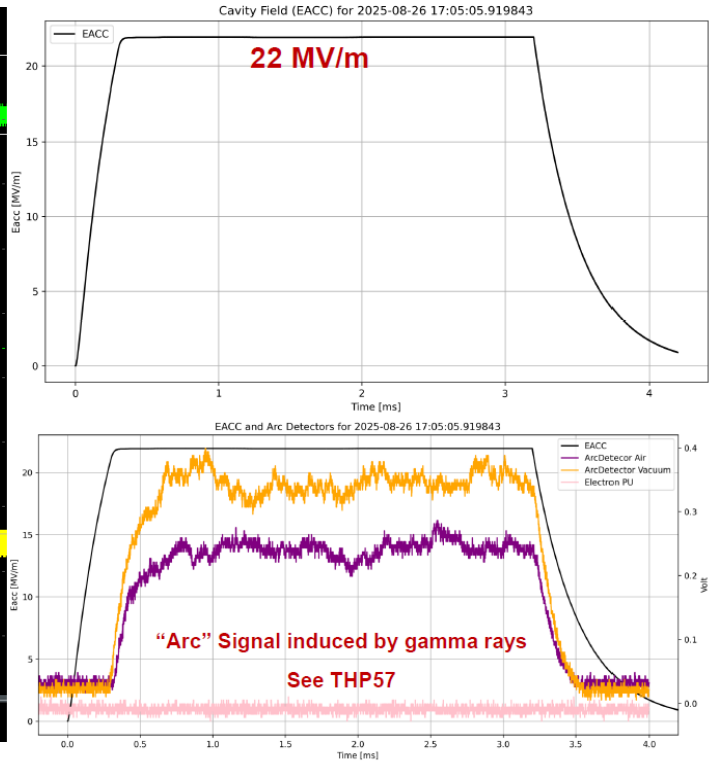
Response of a on blind-terminated 12 m long PMMA optical fiber subjected to cryomodule radiation only (CM08 - CA1 operated at 15 MV/m, 500 µs RF pulses)







Spurious response of FPC2 ADU (CM47 – CAV4 at 22 MV/m)



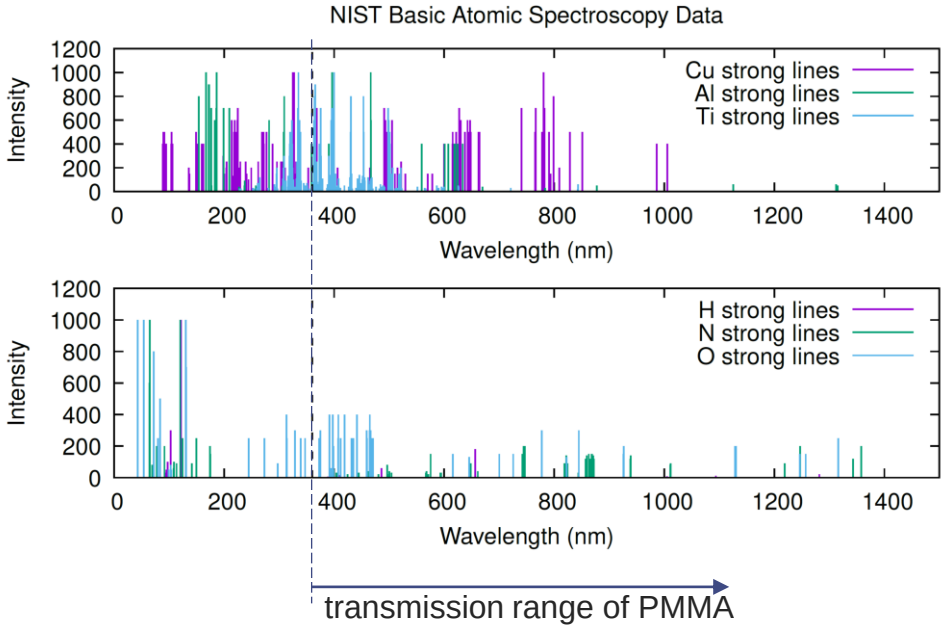
- ~ 4500 light pulses detected
- order of magnitude of rate of events : 1 MHz

When detected with ADU with typical 10µs response time
→ continuous signal

How to discriminate between real/spurious ADU signals?

Can we use spectral filtering on the optical signal output by optical fibers ?

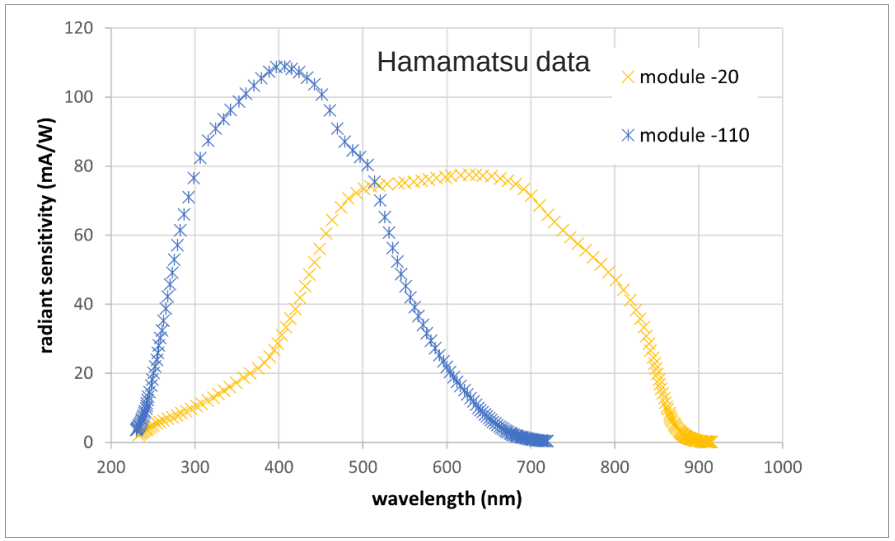
- take advantage of the known $1/\lambda^2$ spectral distribution of Cherenkov radiation
- spectrum of light emitted in FPC is not determined
  - Tentative measurements with off-the-shelf CCD-based optical spectrum analyser failed
  - Considering FPC constitutive materials Cu, Al_2O_3,TiN_xO_y we can expect a complex spectrum extending up to NIR
  - Using successive optical long-pass filters and PMT with two different spectral response, the FPC emission on the vacuum-side was confirmed to contain significant red component

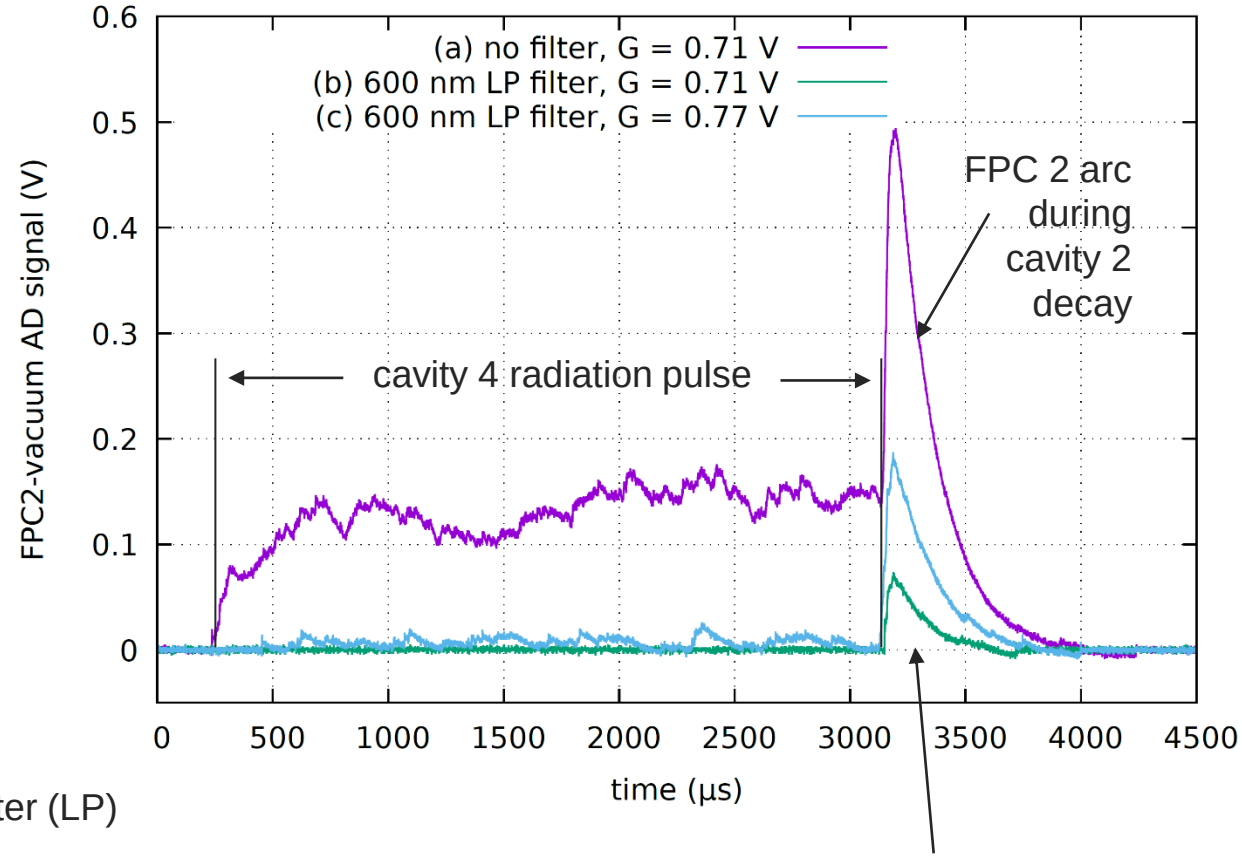


How to discriminate between real/spurious ADU signals?

Strategy for experimental tests :

- take advantage of Cerenkov spectrum $1/\lambda^2$ dependency
- shift the spectral sensitivity of ADU photomultipliers towards red





- filter out the optical signal at shorter wavelengths using a longpass filter (LP)
  - preliminary tests on Saclay FPC test stand showed ADU signal still measurable with the combination of LP filter at 500 nm then 600 nm and 'extended-red' PMTs
  - Proof of principle test at ESS TS2 on CM47 at TS2:
    - Cavity 4 generates radiation with maximum impact on FPC2 fibers → ***spurious signal***
    - Cavity 2 runs at lower gradient with a measurable vacuum arc signal → ***real signal***

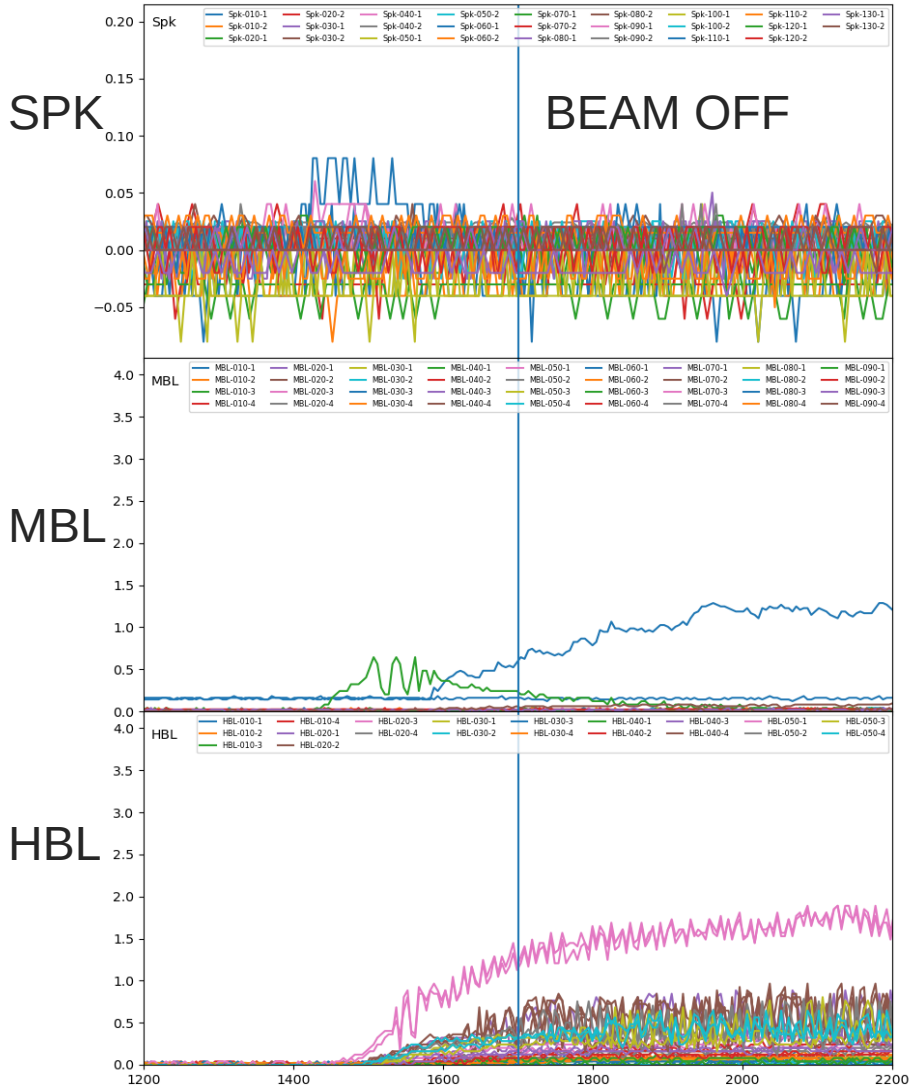
successful improvement of arc/parasitic signal ratio achieved by a factor of 7 with the 600 nm LP filter

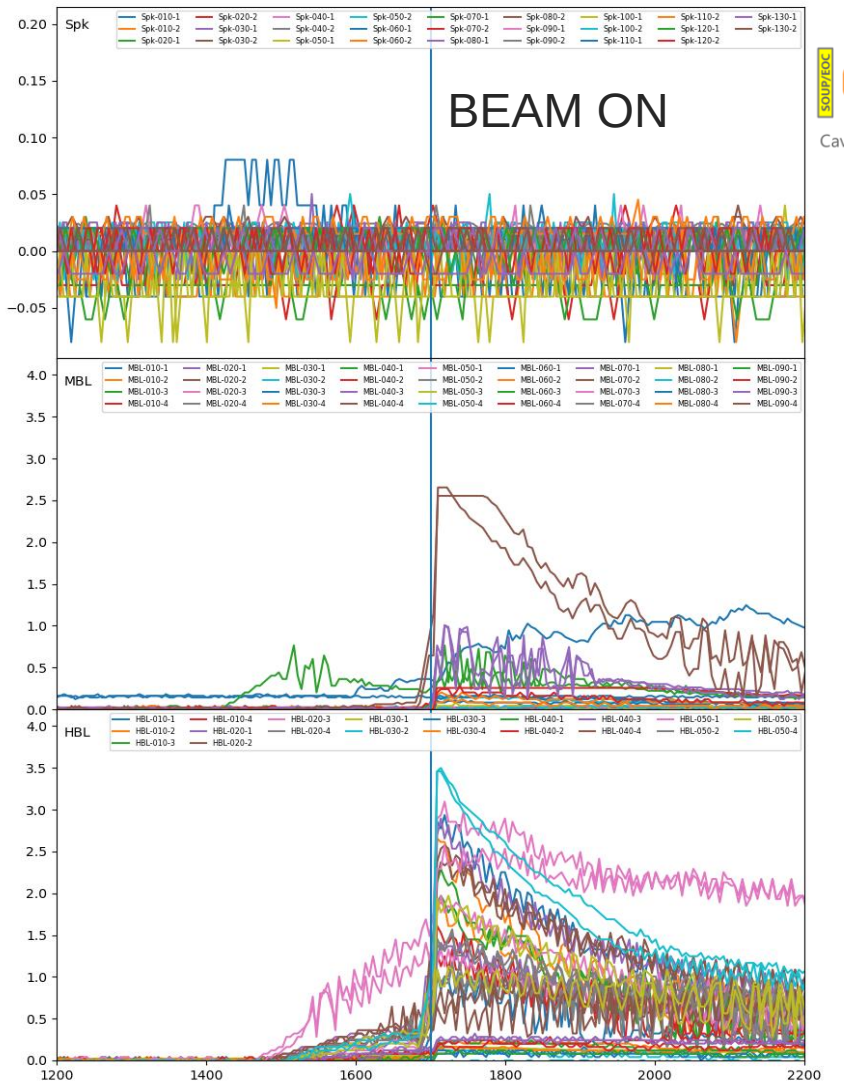
Neutron related spurious arc signals – Linac tunnel

SPK

MBL

HBL





2025 BOD-1
controlled beam losses run

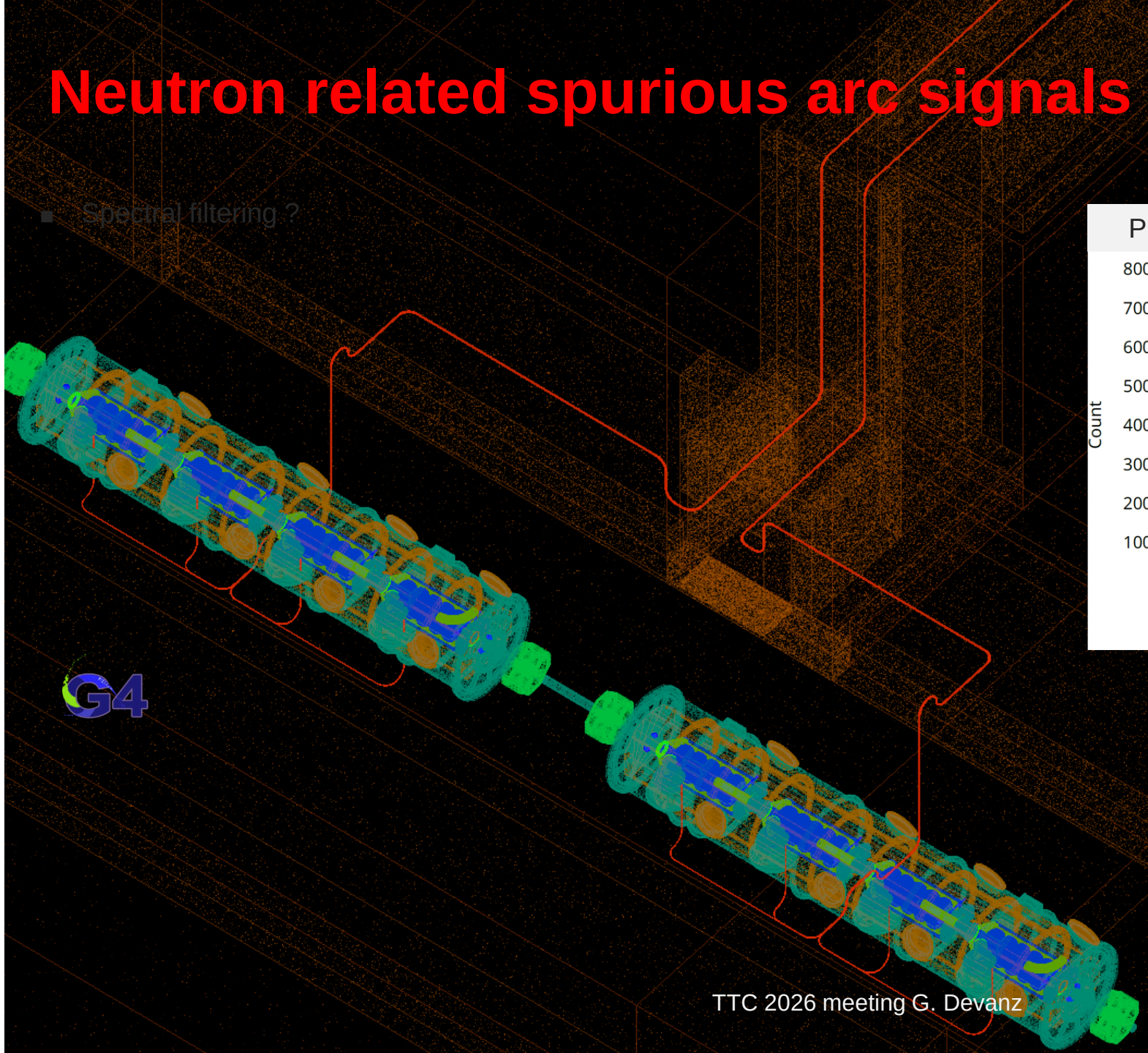
5 µs beam, Ib < 6 mA

Arc detector signals

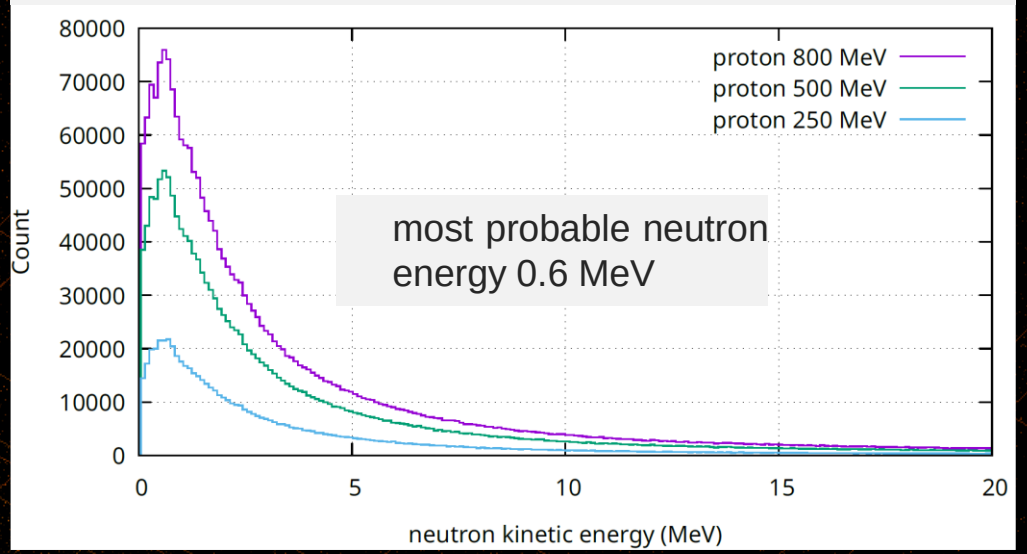
Data : ESS SRF team

Neutron related spurious arc signals – Linac tunnel

- Spectral filtering ?



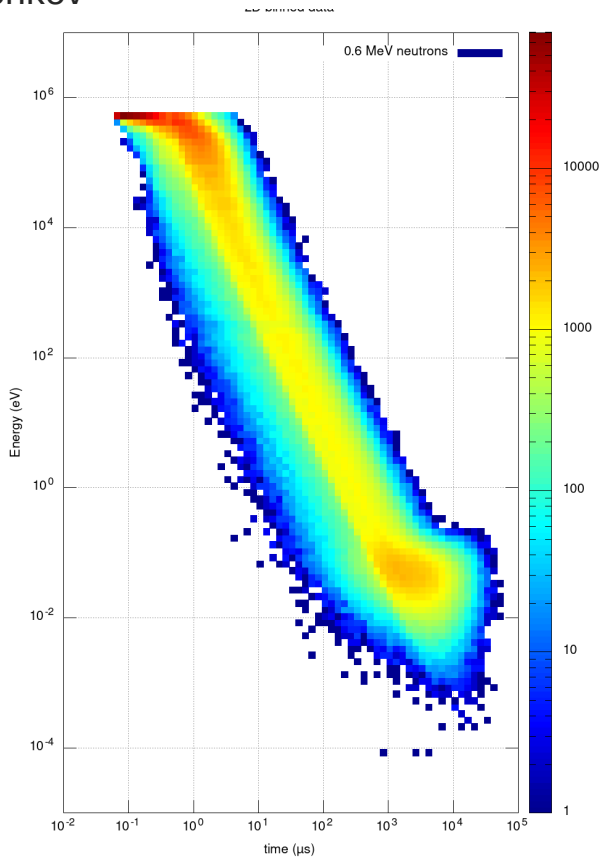
Proton beam loss – generated neutron spectrum

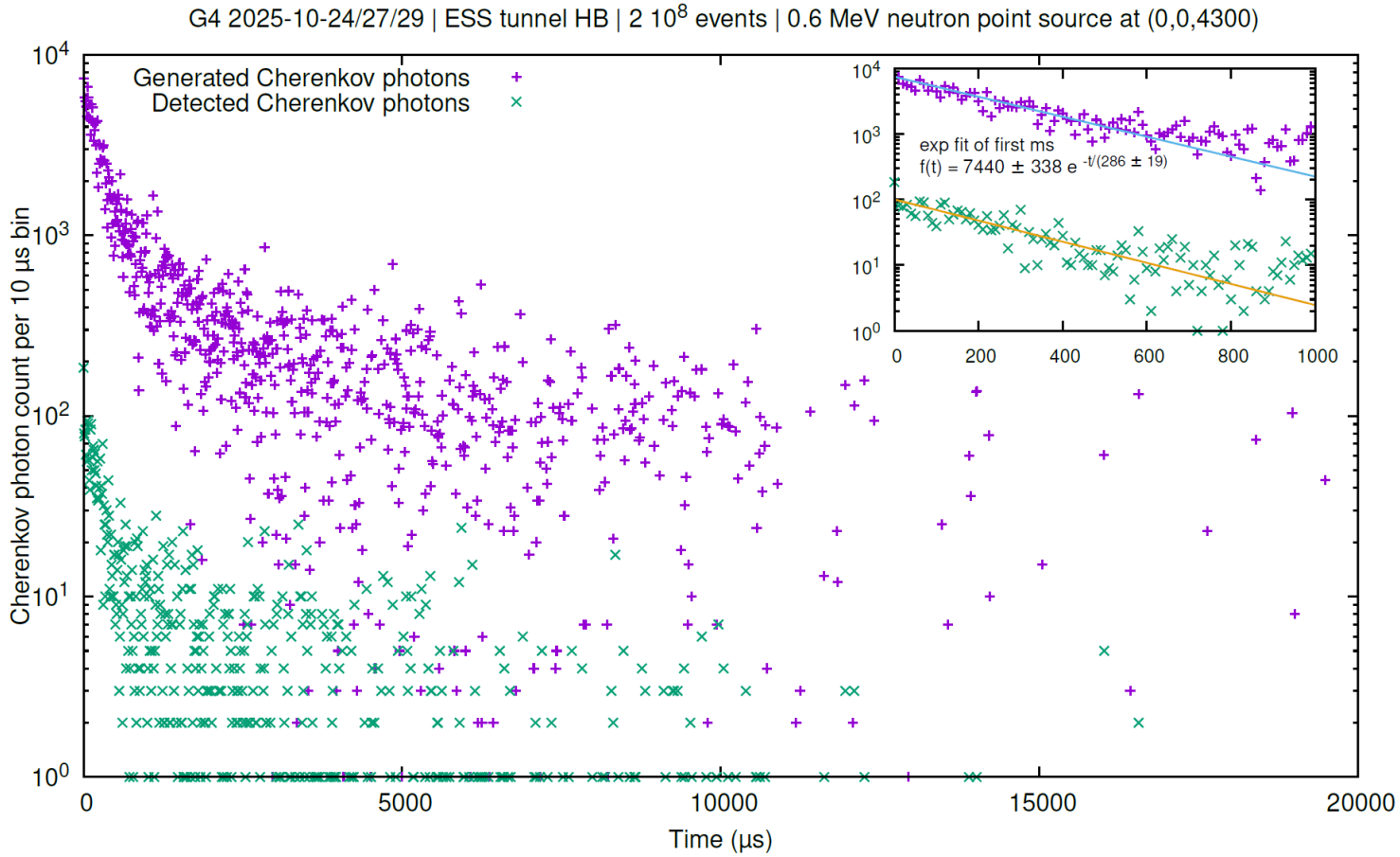


Simulation of a 0.6 MeV neutron point source

The decaying optical signal in the arc detection fbers with this sequence:

- neutron propagation in the tunnel
- neutron moderation mainly in shielding
- neutron capture → γ emission
- as previously described interaction in optical fibers → Cherenkov

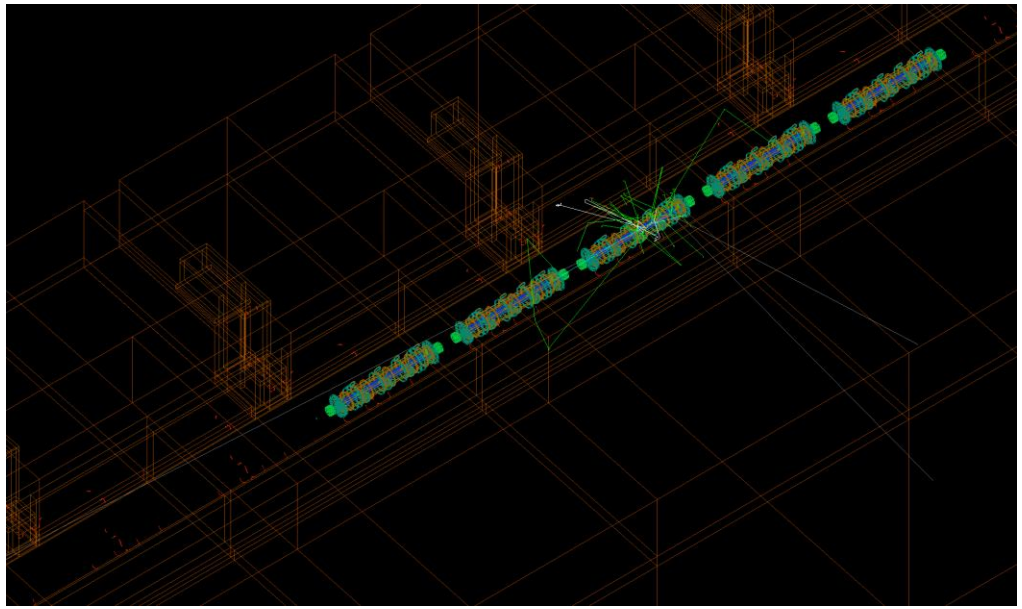




- The first phase of the decay time in the order of hundreds of µs
- its value depends on concrete composition

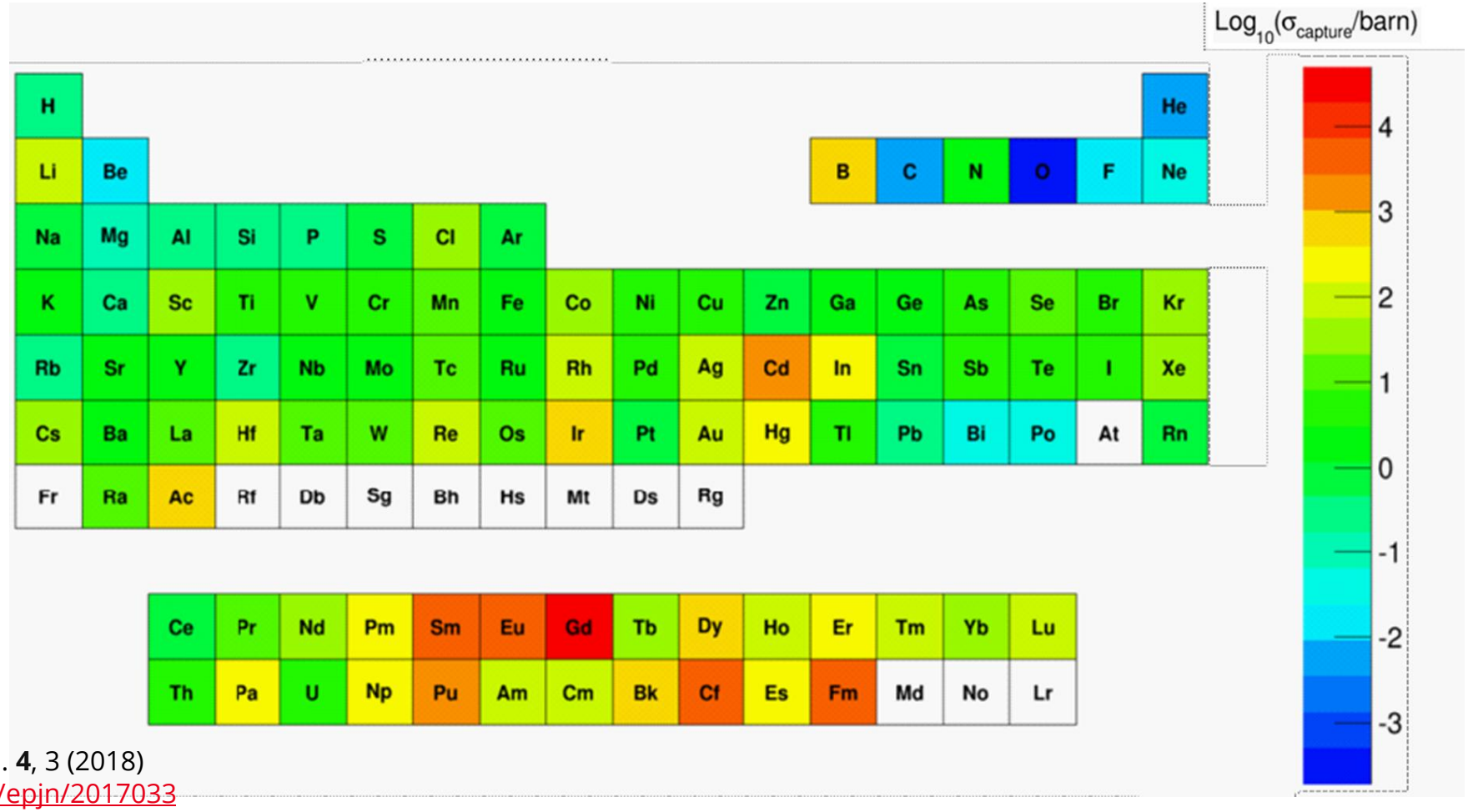
Outlook

- Up to now, focus on the interaction of radiation with FPC arc detection system
- Some progress in mitigating the issue in the case of vacuum-side arcs by changing the arc detectors spectral sensitivity range
- Started the development of instrumentation to study FPC arc spectrum in order to optimize further the targeted spectral range
- Prepare for linac-scale simulation



Extra slides

Cross sections of radiative capture for thermal neutrons



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The characterization of radioactive waste: a critical review of techniques implemented or under development at CEA, France

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